IFUM-818/FT

POLARIZED STRUCTURE FUNCTIONS WITH NEUTRINO BEAMS

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We review the potential impact of neutrino data on the determination of the spin structure of the nucleon. We show that a flavour decomposition of the parton structure of the nucleon as required by present-day precision phenomenology could only be achieved at a neutrino factory. We discuss how neutrino scattering data would allow a full resolution of the nucleon spin problem.

Invited plenary talk at
SPIN 2004
Trieste, November 2004
to be published in the proceedings

1. Physics with neutrino beams

Physics with neutrino beams has played a crucial role in establishing the standard model and its structure, specifically in leading to the discovery of weak neutral currents and of their properties.[1] Currently, while the physics *of* neutrinos gives us the first evidence of physics beyond the standard model[2], the use of neutrinos as probes appears to be the only way of accessing subtle details of the structure of the standard model, on the one hand, and of the nucleon, on the other hand. This is due to the obvious fact that weak currents, unlike the electromagnetic current, couple nontrivially to spin and flavour.

Current data offer tantalizing evidence of this situation: neutrino scattering data from the NuTeV collaboration[3] provide evidence for unexpected

effects, either in the standard model, or in the structure of the nucleon.[4] However, existing beams are insufficient to exploit the potential of neutrino probes, because of scarce intensity and lack of control of the beam spectrum, due to the fact that neutrinos are obtained from the decay of secondary beams (pions). This has recently led to several proposals of facilities where neutrinos would be produced as decay products of a primary beam: either muons (neutrino factories [5]) or radioactive nuclei (β–beams [6]). This would allow the production of $\sim 10^{20}$ neutrinos/year (neutrino factory) or $\sim 10^{18}$ neutrinos/year (β-beam) with full control of the energy spectrum, to be compared to $\sim 10^{16}$ neutrinos/year of present-day experiments. The prospects for the construction of such facilities, which are being studied in Europe, Japan and the U.S.A, have recently improved, in particular due to a renewed commitment of CERN towards future neutrino facilities.[7]

2. Deep-inelastic scattering with neutrino beams

2.1. *Structure functions and parton distributions*

Inclusive DIS is the standard way of accessing the parton content of hadrons. The use of neutrino beams allows one to study DIS mediated by the weak, rather than electromagnetic interaction. The neutrino-nucleon deep-inelastic cross section for charged–current interactions, up to corrections suppressed by powers of m_p^2/Q^2 is given by

$$\begin{aligned}\frac{d^2\sigma^{\lambda_p\lambda_\ell}(x,y,Q^2)}{dxdy} &= \frac{G_F^2}{2\pi(1+Q^2/m_W^2)^2}\frac{Q^2}{xy}\Bigg\{\left[-\lambda_\ell\, y\left(1-\frac{y}{2}\right)xF_3(x,Q^2)\right.\\ &\left.+(1-y)F_2(x,Q^2)+y^2xF_1(x,Q^2)\right]-2\lambda_p\left[-\lambda_\ell\, y(2-y)xg_1(x,Q^2)\right.\\ &\left.-(1-y)g_4(x,Q^2)-y^2xg_5(x,Q^2)\right]\Bigg\}, \qquad (1)\end{aligned}$$

where λ are the lepton and proton helicities (assuming longitudinal proton polarization), and the kinematic variables are $y = \frac{p\cdot q}{p\cdot k}$ (lepton fractional energy loss), $x = \frac{Q^2}{2p\cdot q}$ (Bjorken x). The neutral–current cross–section is found from Eq. (1) by letting $m_W \to m_Z$ and multiplying by an overall factor $[\frac{1}{2}(g_V - \lambda_\ell g_A)]^2$.

The advantage of W and Z-mediated DIS over conventional γ^* DIS is clear when inspecting the parton content of the polarized and unpolarized structure functions F_i and g_i. Up to $O(\alpha_s)$ corrections, in terms of the unpolarized and polarized quark distribution for the i–th flavor $q_i \equiv q_i^{\uparrow\uparrow} + q_i^{\uparrow\downarrow}$ and $\Delta q_i \equiv q_i^{\uparrow\uparrow} - q_i^{\uparrow\downarrow}$

$$
\begin{array}{lcc}
\text{NC} & F_1^{\gamma} = \frac{1}{2}\sum_i e_i^2\,(q_i + \bar{q}_i) & g_1^{\gamma} = \frac{1}{2}\sum_i e_i^2\,(\Delta q_i + \Delta\bar{q}_i) \\
\text{NC} & F_1^{Z} = \frac{1}{2}\sum_i (g_V^2 + g_A^2)_i\,(q_i + \bar{q}_i) & g_1^{Z} = \frac{1}{2}\sum_i (g_V^2 + g_A^2)_i\,(\Delta q_i + \Delta\bar{q}_i) \\
\text{NC} & F_3^{Z} = 2\sum_i (g_V g_A)_i\,(q_i + \bar{q}_i) & g_5^{Z} = -\sum_i (g_V g_A)_i\,(\Delta q_i + \Delta\bar{q}_i) \\
\text{CC} & F_1^{W^+} = \bar{u} + d + s + \bar{c} & g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c} \\
\text{CC} & -F_3^{W^+}/2 = \bar{u} - d - s + \bar{c} & g_5^{W^+} = \Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c} \\
 & F_2 = 2xF_1 & g_4 = 2xg_5
\end{array}
$$

Here e_i are the electric charges and $(g_V)_i$, $(g_A)_i$ are the weak charges of the i–th quark flavor. If $W^+ \to W^-$ (incoming $\bar{\nu}$ beam), then $u \leftrightarrow d$, $c \leftrightarrow s$. Of course, beyond leading order in the strong coupling each quark or antiquark flavor's contribution receives $O(\alpha_s)$ corrections proportional to itself and to all other quark, antiquark and gluon distributions. However, the gluon correction is flavor–blind, and thus decouples from the parity–violating structure functions F_3, g_4 and g_5.

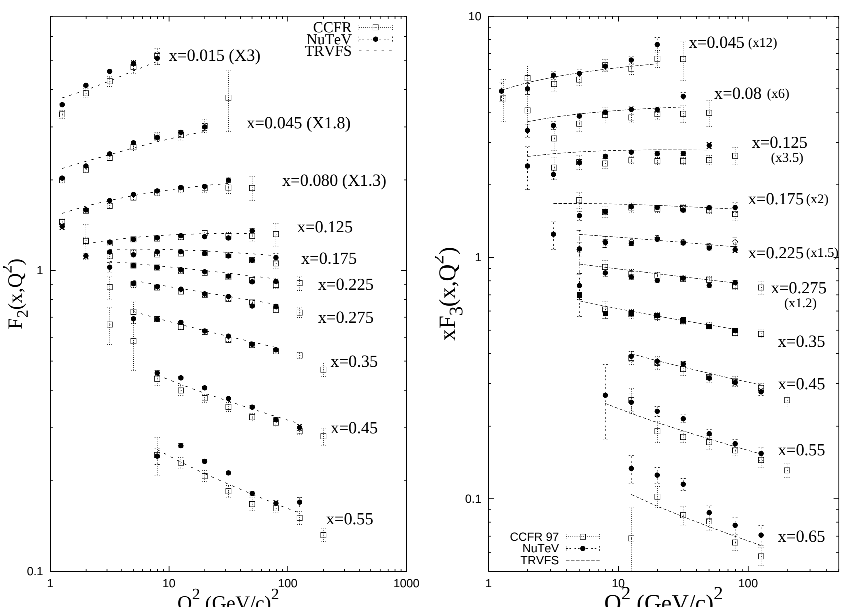

Figure 1. Current unpolarized proton structure functions from μ scattering (from ref. [10]). The structure functions shown are $\nu + \bar{\nu}$ averages.

In neutral current DIS only the C-even combinations $q_i + \bar{q}_i$ and $\Delta q_i + \Delta\bar{q}_i$ are accessible. Furthermore, the structure functions F_3, g_4 and g_5 are parity–violating, and therefore not accessible in virtual photon scattering. In the presence of weak couplings, more independent linear

combination of individual quark and antiquark distributions are accessible, thereby allowing one to disentangle individual flavours and antiflavours. [8,9]

2.2. *Current data and future prospects*

Structure function measurements with neutrino beams have been performed recently by the CCFR/NuTeV collaboration,[10] while DIS results have been announced, but not yet published, by the CHORUS[11] and NOMAD[12] collaborations. Older results, including historic bubble–chamber data, have been reanalized and collected in ref.[13]. The recent NuTeV structure function data, based on a sample of 8.6×10^5 ν and 2.3×10^5 $\bar{\nu}$ DIS events, have led to reasonably precise determinations of the structure functions F_2 and F_3 (see fig.1). However, they still have rather lower accuracy than charged-lepton DIS data. Furthermore, only $\nu+\bar{\nu}$ structure function averages are determined: $F_3^{\nu}+F_3^{\bar{\nu}}$ (compare eq. (1)), from the difference $\sigma^{\nu}-\sigma^{\bar{\nu}}$, and $F_2^{\nu}+F_2^{\bar{\nu}}$ from the average $\sigma^{\nu}+\sigma^{\bar{\nu}}$ using a theoretical determination of F_3. Hence, results are not free from theoretical assumptions, and only some linear combinations of parton distributions are accessible. Finally, present-day neutrino target–detectors are very large in order to ensure reasonable rates with available beams: e.g. the NuTeV target-calorimeter consists of 84 iron plates, 10 m×10 m×10 cm. Clearly, this prevents the possibility of putting the target inside a polarizing magnet.

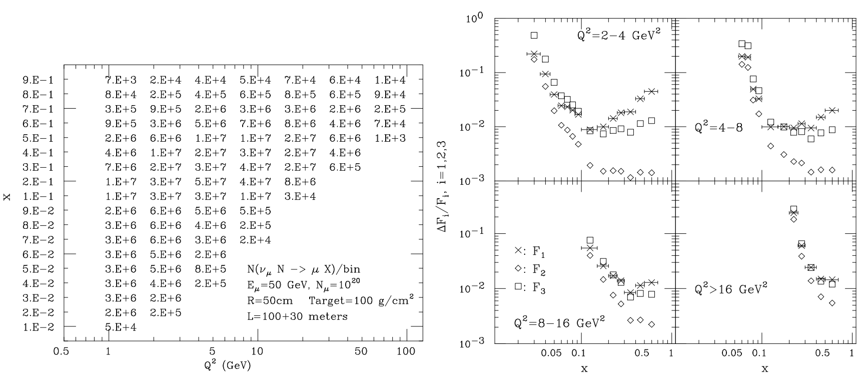

Figure 2. Unpolarized DIS event rates (left) and errors on unpolarized parton distributions (right) for one year of running in the CERN neutrino factory scenario (from ref. [14]).

At a neutrino factory (in the CERN scenario[5,14]) the neutrino beam originates from the decay of 10^{20} μ per year, stored in a 50 GeV ring.

With a target effective density of 100 g/cm^2, corresponding to, say, a 10 m long deuterium target[8] and a radius of 50 cm, one could then count on 5×10^8 DIS events per year, with the rates in individual bins shown in fig.2. Furthermore, taking advantage of the fact that $y = Q^2/(2xm_pE_\nu)$, at fixed x and Q^2, y varies with the incoming ν energy. Because the beam at a neutrino factory is broad-band, if the kinematics of the DIS event can be fully reconstructed on an event-by-event basis, it is then possible to disentangle the contributions of the individual structure functions to the cross section Eq. (1) by fitting the y dependence of the data for fixed x and Q^2. The errors on individual structure functions obtained through such a procedure are shown in fig.2, and are in fact rather smaller than those on current charged-lepton DIS structure functions.

Recent results of the NuTeV collaboration on the CC/NC total neutrino DIS cross sections highlight the potential and limitations of current neutrino data. The NuTeV data[3] allow a determination of the Paschos-Wolfenstein[15] ratio

$$\begin{aligned} R^- &= \frac{\sigma_{NC}(\nu) - \sigma_{NC}(\bar\nu)}{\sigma_{CC}(\nu) - \sigma_{CC}(\bar\nu)} \\ &= \left(\frac{1}{2} - \sin^2\theta_W\right) + 2\left[\frac{(u-\bar u)-(d-\bar d)}{u-\bar u+d-\bar d} - \frac{s-\bar s}{u-\bar u+d-\bar d}\right]\times \qquad (2) \\ &\quad \left[\left(\frac{1}{2} - \frac{7}{6}\sin^2\theta_W\right) + \frac{4}{9}\frac{\alpha_s}{2\pi}\left(\frac{1}{2}-\sin^2\theta_W\right) + O(\alpha_s^2)\right] + O(\delta(u-d)^2,\ \delta s^2) \end{aligned}$$

where u, d, s, etc. denote the second moments of the corresponding parton distributions. All dependence on parton distributions disappears assuming isospin for an isoscalar target, if one also assumes $s = \bar s$ (which is nontrivial for second moments).

Using these assumptions, NuTeV has arrived at a determination of $\sin^2\theta_W$ which differs by about three sigma from the current standard best-fit. This indicates either physics beyond the standard model, or a nucleon structure which is subtler than expected.[4] Small violations of isospin are produced by QED corrections, and in fact phenomenological evidence supports an isospin violation which reduces the observed discrepancy by about one σ.[16] Also, a global fit to world data favors a strangeness asymmetry of the size and magnitude required to remove the effect entirely.[17] However, in both cases the null assumption which leads to the discrepancy with the standard model cannot be really excluded within the required precision. Whereas less inclusive data, such as W production at hadron colliders, might give us some extra handle on the flavor decomposition of parton

distributions,[18] only a neutrino factory would allow a full determination of the flavour and antiflavour content of the nucleon[14] as required for this kind of precision physics.

3. Polarized physics with neutrino beams

3.1. *Polarized DIS and the proton spin puzzle*

The determination of the polarized structure of the nucleon has progressed considerabily since the surprizing discovery of the smallness of the nucleon's singlet axial charge a_0.[20] The focus of current phenomenological activity has shifted from inclusive deep-inelastic scattering to less inclusive data, largely driven by the desire to access quantities, such as transversity, which decouple from inclusive DIS. Whereas semi-inclusive data give us some hint of the flavour structure of the nucleon,[21] experience in the unpolarized case[18] teaches that they cannot compete in accuracy with DIS data, while hadron collider data play a complementary role.

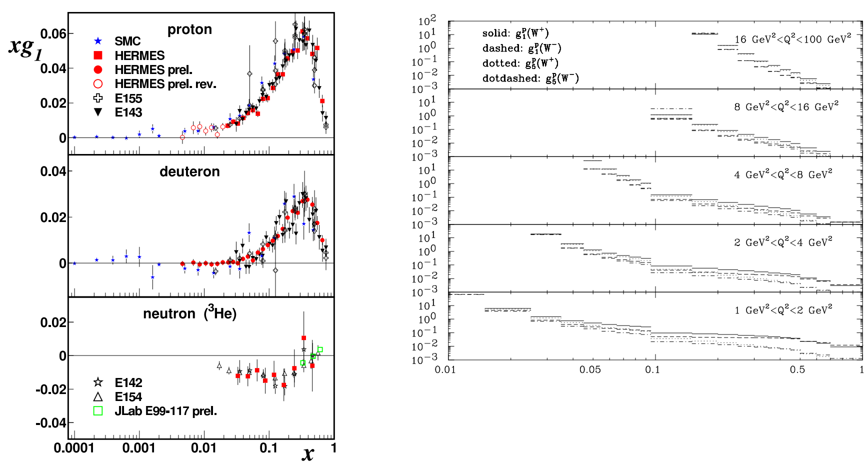

Figure 3. Current polarized structure function data (left, from ref. [19]) and expected accuracies in the CERN neutrino factory scenario (right, from ref. [14]).

However, a detailed understanding of the flavour and antiflavour content of the nucleon is mandatory if one wishes to elucidate its spin structure.[22] Indeed, the reason why the smallness of the singlet axial charge a_0 is surprizing is that it signals a departure from the quark model, in which a_0

is the total quark spin fraction, and $a_0 \approx a_8$, the difference being due to the strange contribution, which is expected to be small by the Zweig rule. The octet axial charge a_8 cannot in practice be determined from neutral-current DIS data, hence it is currently determined using SU(3) from baryon β–decay constants: $a_8 = 0.6 \pm 30\%$, while $a_0 = 0.10^{+0.17}_{-0.11}$ (at $Q^2 = \infty$). Whereas a_8 does not depend on Q^2, a_0 does: because of the axial anomaly, $\partial_\mu j_5^\mu \neq 0$. It turns out, however, that it is possible to choose a factorization scheme in such a way that the quark distribution is scale–independent. In such case a_0 and the total quark spin fraction $\Delta\Sigma$ are no longer equal:

$$\begin{aligned} a_3 &= \Delta u + \Delta\bar{u} - (\Delta d + \Delta\bar{d}) \\ a_8 &= \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s}) \\ \Delta\Sigma &= \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \\ a_0 &= \Delta\Sigma - \frac{n_f \alpha_s}{2\pi}\Delta G \end{aligned} \tag{3}$$

where Δq_i and ΔG are respectively the quark and gluon spin fractions.

One can then envisage various scenarios for the nucleon spin content.[22,9] A first possibility is that perhaps, even though a_0 is small, $\Delta\Sigma$ eq. (3) is large, because $\alpha\Delta g$ is large ('anomaly' scenario). If instead $\alpha\Delta g$ is small, there are two possibilities. Either the determination of a_8 from octet decays using isospin is incorrect, the Zweig rule in actual fact holds, $a_0 \approx a_8$, and the strange spin fraction $\Delta s + \Delta\bar{s}$ is small. Else, $\Delta s + \Delta\bar{s}$ is large, i.e. comparable to $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$. This is predicted for instance to happen in instanton models or in Skyrme models. These two cases, however, predict respectively that Δs and $\Delta\bar{s}$ are separately large ('instanton' scenario) or that $\Delta s \ll \Delta\bar{s}$ ('skyrmion' scenario). In short different models of the nucleon spin structure lead to distinct predictions for its polarized content.

Table 1. Quark and gluon first moments. Both statistical and systematic errors are given for current values (from ref. [23]) statistical only for the neutrino factory scenarios (from ref. [9]).

	present	anomaly	instanton	skyrmion
Δg	$0.8 \pm 0.2 \pm 0.4$	0.86 ± 0.10	0.20 ± 0.06	0.24 ± 0.08
$\Delta\Sigma$	$0.38 \pm 0.03 \pm 0.04$	0.39 ± 0.01	0.321 ± 0.006	0.324 ± 0.008
a_3	$1.11 \pm 0.04 \pm 0.04$	1.097 ± 0.006	1.052 ± 0.013	1.066 ± 0.014
a_8	$0.6 \pm 0.2(?)$	0.557 ± 0.011	0.572 ± 0.013	0.580 ± 0.012
$\Delta s - \Delta\bar{s}$	?	-0.075 ± 0.008	-0.007 ± 0.007	-0.106 ± 0.008

Current data provide a fairly accurate determination of $g_1^\gamma(x, Q^2)$ (figure 3). From these only the C-even combination $\Delta q_i + \Delta\bar{q}_i$ can be determined, while Δg can be extracted from scaling violations, albeit with large errors.[23] A reasonably accurate determination of the isotriplet component is then possible, especially its first moment. However, the individual valence flavours can be determined much less accurately, partly because of their admixture with the gluon eq. (3). In fact, only first moments can be determined with reasonable accuracy (table 1), while the shape of individual parton distributions is only known rather poorly (figure 4).

3.2. *The spin of the nucleon at a neutrino factory*

At a neutrino factory, significant rates could be achieved with small targets:[8] even with a rather conservative effective density of 10 g/cm^2, with a detector radius of 50 cm, the structure functions g_1, g_5 could still be independently measured with an accuracy which is about one order of magnitude better than that with which g_1 is determined in present charged lepton DIS experiments (figure 3). On the basis of such data, the flavour structure of the nucleon could be entirely disentangled:[23] in particular, the difference of any two flavour or antiflavour fractions could be determined, typically with uncertainties of order of 1% (table 1).

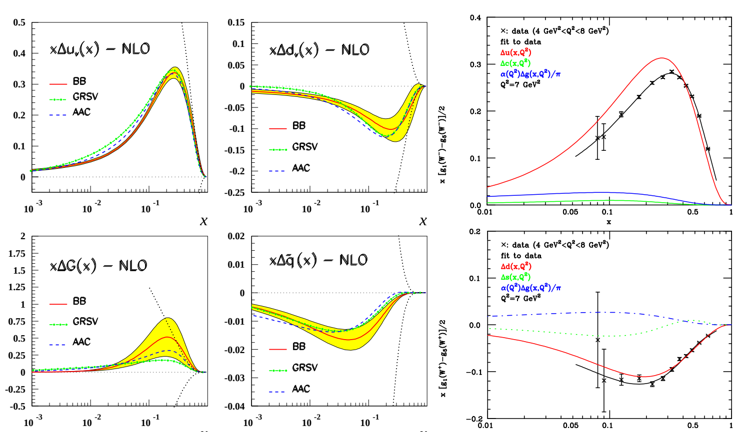

Figure 4. Current errors on polarized parton distributions (left, from ref. [24]) and expected errors in the CERN neutrino factory scenario (right, from ref. [9]).

The absolute value of each quark distribution, however, is affected by the

gluon admixture eq. (3). Therefore, the precision in the determination of a_0 is set by the accuracy in the knowledge of Δg. The determination of the latter at a neutrino factory would improve somewhat thanks to the accurate knowledge of scaling violations, but it would be very significantly hampered by the limited kinematic coverage, in Q^2 and especially at small x. On the other hand, by the time a neutrino factory comes into operation Δg is likely to have been determined at collider experiments, such as RHIC.[20] Hence, hadron colliders and the neutrino factory have complementary roles. The same applies to the determination of the shape of individual parton distributions (figure 4). While structure functions would be measured very accurately, the dominant uncertainty of quark distributions would come from the polarized gluon.

Less inclusive measurements at a neutrino factory could provide a very clean handle on individual observables: for example, strangeness could be studied through charm production, just as in the unpolarized case. Thanks to high event rates, it would be possible to measure even elusive quantities such as related to polarized fragmentation, or even generalized parton distributions.[14]

4. Do we need a neutrino factory?

Alternative high–intensity neutrino sources, such as β beams, provide attractive opportunities for the study of neutrino oscillations. They share the same advantages as the neutrino factory, but with a somewhat lower flux and much lower energy: e.g. at a β beam one would expect $\sim 10^{18}$ β decays per year with an average ν energy $\sim$ 200 MeV. With such a beam only elastic or quasi-elastic scattering on nucleons can be performed. However, effective field theory results[26] relate the matrix elements measured in low-energy scattering to polarized partonic observables: e.g. $\langle p|j_5^{\mu\,Z}|p\rangle = \Delta u - \Delta d - \Delta s = -\frac{1}{3}a_0 + a_3 + \frac{1}{3}a_8$, up to computable corrections related to higher-dimensional operators. This would allow e.g. a direct determination of a_8 and thus of the total polarized strangeness, if not the separation of Δs and $\Delta \bar{s}$. The full impact of such measurements on high-energy nucleon observables is currently under investigation.[27]

In sum, a full determination of the polarized flavour structure of the nucleon will only be possible at a neutrino factory, with collider data providing complementary information on the polarized glue. Low-energy facilities such as β–beams would have a more limited though not negligible impact.

Acknowledgments

I thank F. Bradamante for inviting me at this stimulating meeting. This work was completed at KITP Santa Barbara, supported in part by the National Science Foundation under grant PHY99-0794.

References

1. See e.g. A. De Rujula, in "Fifty years of Yang-Mills theories" (G. 't Hooft, ed), World Scientific, Singapore 2004; `hep-ph/0404215`, and ref. therein.
2. See e.g. G. Altarelli, `hep-ph/0410101` and ref. therein.
3. G. P. Zeller *et al.* [NuTeV Collaboration], Phys. Rev. Lett. **88** (2002) 091802 [Erratum-ibid. **90** (2003) 239902]
4. S. Davidson, S. Forte, P. Gambino, N. Rius and A. Strumia, JHEP **0202** (2002) 037
5. See A. Blondel *et al.*, CERN-2004-002; T. Adams *et al.*, `hep-ph/0111030` and ref. therein.
6. P. Zucchelli, Phys. Lett. B **532** (2002) 166; see also M. Mezzetto, `hep-ex/0410083` and ref. therein.
7. See J. Dainton, `http://hep.ph.liv.ac.uk/~jbd/CERN_seminar_Villars_released_public.ppt`
8. R. D. Ball, D. A. Harris and K. S. McFarland, `hep-ph/0009223`.
9. S. Forte, M. L. Mangano and G. Ridolfi, Nucl. Phys. B **602** (2001) 585.
10. D. Naples *et al.* [NuTeV Collaboration], `hep-ex/0307005`.
11. R. G. C. Oldeman [CHORUS Collaboration], Nucl. Phys. Proc. Suppl. **79** (1999) 96;
12. R. Petti [NOMAD Collaboration], `hep-ex/0411032`.
13. V. Barone, C. Pascaud and F. Zomer, Eur. Phys. J. C **12** (2000) 243.
14. M. L. Mangano *et al.*, `hep-ph/0105155`.
15. E. A. Paschos and L. Wolfenstein, Phys. Rev. D **7** (1973) 91.
16. A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne, `hep-ph/0411040`;
    Eur. Phys. J. C **35** (2004) 325.
17. F. Olness *et al.*, `hep-ph/0312323`.
18. See e.g. W. K. Tung, `hep-ph/0409145` and ref. therein.
19. U. Stösslein, Acta Phys. Polon. B **33** (2002) 2813.
20. See W. Vogelsang, `hep-ph/0405069`;
    A. Metz, `hep-ph/0412156`, *these proceedings*, and ref. therein.
21. A. Airapetian *et al.* [HERMES Collaboration], `hep-ex/0407032`; D. Hasch, *these proceedings*;
    E. Christova and E. Leader, Nucl. Phys. B **607** (2001) 369; `hep-ph/0412150`, *these proceedings*.
22. S. Forte, `hep-ph/9409416`; `hep-ph/9610238`.
23. G. Altarelli, R. D. Ball, S. Forte and G. Ridolfi, Nucl. Phys. B **496** (1997) 337; Acta Phys. Polon. B **29** (1998) 1145;
    G. Ridolfi, eConf **C030614**, 019 (2003).

24. J. Blümlein and H. Böttcher, Nucl. Phys. B **636** (2002) 225.
25. Y. Goto et al. [Asymmetry Analysis Collaboration], Phys. Rev. D **62** (2000) 030417
26. D. B. Kaplan and A. Manohar, Nucl. Phys. B **310** (1988) 527.
27. P. Ferrario and S. Forte, *in preparation*.